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Metamodels for Composite Lattice Fuselage Design

Dianzi Liu, Xue Zhou, and Vassili Toropov

Abstract—This paper presents a novel design of an anisogrid composite aircraft fuselage by a global metamodel-based optimization approach. A 101-point design of numerical experiments (DOE) has been developed to generate a set of individual fuselage barrel designs and these designs have further been analyzed by the finite element (FE) method. Using these training data, global metamodels of all structural responses of interest have been built as explicit expressions of the design variables using a Genetic Programming approach. Finally, the parametric optimization of the fuselage barrel by genetic algorithm (GA) has been performed to obtain the best design configuration in terms of weight savings subject to stability, global stiffness and strain requirements.

Index Terms—Composite fuselage structure, anisogrid design, genetic programming, metamodel.

I. INTRODUCTION

In order to keep air transport competitive and safe, aircraft designers are forced for minimum weight and cost designs. Carbon composite materials combined with lattice structures for the next generation fuselage design have the potential to fulfill these requirements. This novel design of a lattice composite fuselage has been investigated recently for a new weight-efficient composite fuselage section [1].

Based on the conceptual fuselage design obtained by topology optimization with respect to weight and structural performance [2], [3], the parametric optimization of the composite lattice fuselage to obtain the optimal solution describing the lattice element geometry is performed in this paper. This detailed design process is a multi-parameter optimisation problem, for which a metamodel-based optimization technique is used to obtain the optimal lattice element geometry. Since one of the design variables, the number of helical ribs, is integer in the optimization of a lattice composite fuselage structure, a discrete form of genetic algorithm (GA) [4], [5] is used to search for the optimal solution in terms of weight savings subject to stability, global stiffness and strain requirements. Finally, the skin is interpreted as a practical composite laminate which complies with the aircraft industry lay-up rules and manufacturing requirements.

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II. DESIGN OF EXPERIMENTS

The quality of the metamodel strongly depends on an appropriate choice of the Design of Experiments (DOE) type and sampling size. A uniform Latin hypercube DOE based on the use of the Audze-Eglais optimality criterion [6], is proposed. The main principles in this approach are as follows:

- The number of levels of factors (same for each factor) is equal to the number of experiments and for each level there is only one experiment;
- The points corresponding to the experiments are distributed as uniformly as possible in the domain of factors. There is a physical analogy of the Audze-Eglais optimality criterion with the minimum of potential energy of repulsive forces for a set of points of unit mass, if the magnitude of these repulsive forces is inversely proportional to the squared distance between the points:

$$U = \sum_{p=1}^P \sum_{q=p+1}^P \frac{1}{L_{pq}^2} \rightarrow \min \quad (1)$$

where P is the number of points, L_{pq} is the distance between the points p and q ($p \neq q$) in the system. Minimizing U produces a system (DOE) where points are distributed as uniformly as possible, see Fig. 1.

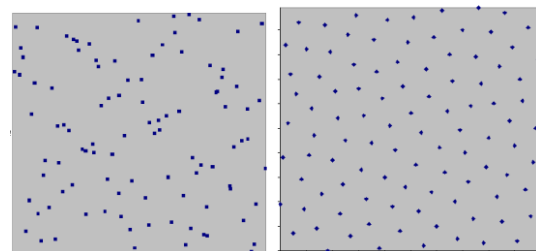


Fig. 1. Designs of experiments (100 points) generated by the conventional (left) and optimal (right) Latin hypercube technique [7].

III. GENETIC PROGRAMMING (GP)

The genetic programming code was first developed according to the guidelines provided by Koza [8], then further implemented by Armani [9]. The common genetic operations used in genetic programming are reproduction, mutation and crossover, which are performed on mathematical expressions stripped of their corresponding numerical values. Since GP methodology is a systematic way of selecting a structure of high quality global approximations, selection of individual regression components in a model results in solving a combinatorial optimization problem. In our case of design optimization, the program represents an empirical model to be used for approximation of a response function. A tree structure-based typical program, representing the

expression $(x_1 / x_2 + x_3)^2$, is shown in Fig. 2.

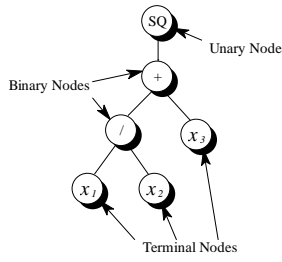


Fig. 2. Typical tree structure for $(x_1 / x_2 + x_3)^2$.

These randomly generated programs are general and hierarchical, varying in size and shape. GP's main goal is to solve a problem by searching highly fit computer programs in the space of all possible programs that solve the problem. This aspect is the key to find near global solutions by keeping many solutions potentially close to minima (local or global). The evolution of the programs is performed through the action of the genetic operators and the evaluation of the fitness function.

IV. FINITE ELEMENT SIMULATIONS AND MARGINS OF SAFETY

Two FE models used in the analysis were based on a relatively coarse mesh and a much finer mesh that corresponds to a converged solution found from a mesh sensitivity study. The coarse mesh FE simulations, that are an order of magnitude faster, still reveal the most prominent features of the structural response and hence have been used in the analysis of 101 designs corresponding to the DOE points. Then, the obtained optimal solution was validated by the analysis with the fine FE mesh.

The measure of strains used were the largest strains in the structure. This consisted of the tensile and compressive strains in the frames and helical ribs, and the tensile, compressive and shears strains in the fuselage skin. These strains are normalization with respect to the maximum allowable strains in the structure. The margin of safety for strain and strength response is defined as:

$$MS_{\varepsilon} = \frac{\varepsilon_{\max}}{\varepsilon} - 1 \geq 0, \quad MS_S = \frac{S}{S_{\min}} - 1 \geq 0, \quad MS_B = \lambda - 1 \geq 0 \quad (2)$$

where MS is Margin of Safety, ε is the computed strain, ε_{\max} is the maximum allowable strain, S is the computed stiffness, S_{\min} the minimum allowable stiffness, λ is the computed linear buckling eigenvalue for the applied loads.

V. DESIGN VARIABLES AND OPTIMIZATION OF FUSELAGE STRUCTURE

The ALaSCA Airframe Concept is a lattice structure with a load bearing skin and stiffeners located on either side of the

skin as shown in Fig. 3. The outer stiffeners are surrounded by protective foam, which in turn is covered by a thin aerodynamic skin [2]. The optimized grid type fuselage section is a simple structure without windows or floors consisting only of the repeated structural triangular unit cell. Fig. 4 shows the finite element fuselage barrel model with the inner helical ribs in green, their counter parts on the outside of the skin in blue, the circumferential frames in yellow and the skin in red. The stiffening ribs are arranged at an angle so as to describe a helical path along the fuselage barrel skin. Hence, these ribs are called helical ribs. The helical ribs have a hat cross section, whereas the circumferential frames have a Z-shaped cross section. These ribs in conjunction with the circumferential frames create uniform triangular skin bays. The helical ribs form an angle of 2ϕ between them as illustrated in Fig. 3. This angle remains constant throughout the barrel model.

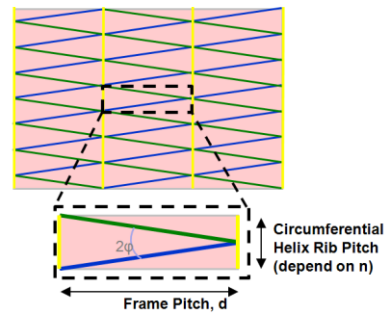


Fig. 3. Skin bay geometry.

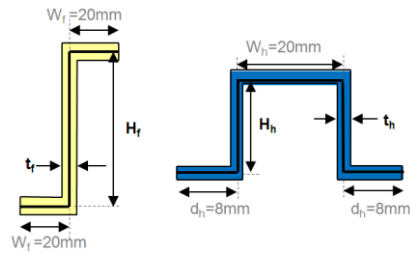


Fig. 4. Circumferential ribs and helical ribs.

The design variables are chosen to vary the geometry of the helical stiffeners and frames, the skin thickness, and the frame pitch without altering the triangular shape of the skin bay geometry. The seven optimization parameters are varied between the maximum and the minimum bounds listed in Table I. The design variables are shown in Fig. 3 and Fig. 4. The optimization constraints are strain, global stiffness and stability. The corresponding optimization responses extracted from the FE models are the largest strains (tensile and compressive strains in the frames and in the helical ribs; tensile, compressive and shear strains in the skin), the critical buckling load, and the stiffness of the fuselage. The composite material fails if it is strained beyond a maximum value. Finally, the fuselage has to have a certain stiffness in bending and in torsion to avoid excessive global deformations in flight. The design variables are varied within the bounds shown in Table I to generate fuselage structures, which are then evaluated with respect to the mentioned failure modes.

An upward gust load case at low altitude and cruise speed is applied to the modelled fuselage barrel and depicted in Fig. 5. At one end of the barrel, bending, shear, and torsion loads are applied while the opposite end is fixed. These loads are

applied via rigid multipoint constraints, which force a rigid barrel end. While floors are not modelled, the masses from the floors are applied at the floor insertion nodes. Finally, the structural masses are applied to the skin shell elements via mass densities.

VI. RESULTS AND DISCUSSIONS

The explicit expressions for the responses related to tensile strain, compressive strain, shear strain and weight of the fuselage barrel are built by GP. As an example, the expression for the shear strain is:

$$f_{ss} = 1.26902 Z_1 - 1.76206 Z_3 + 0.00132105 Z_3 Z_5 + 2.93847 Z_3 / Z_2 + 603.316 Z_3 / Z_5 + 0.00000000604561 Z_1 Z_3 Z_5^2 Z_7 - 4143.98 Z_1^2 / (Z_2^2 Z_4 Z_6) + 163.814 Z_3 Z_4 / (Z_2 Z_5) + 0.202164 Z_2 Z_4^2 Z_6 / (Z_3 Z_7) - 660.152 Z_1^3 / (Z_2 Z_3^2 Z_4 Z_7) - 15.5318 Z_1^2 Z_6 Z_7^4 / (Z_2^4 Z_3^2 Z_4 Z_5) - 0.975381$$

where Z_1 to Z_7 are the design variables detailed in Table I.

TABLE II: STRUCTURAL RESPONSE VALUES FOR THE OPTIMUM DESIGN

Response type	Strain tension	Strain compression	Strain shear	Buckling	Torsional stiffness	Bending stiffness	Normalized mass
Prediction by metamodel	0.20	0.23	1.27	0.00	1.21	0.89	0.29
Fine mesh FE analysis	0.62	0.08	1.09	-0.07	1.21	0.89	0.29
Composite laminate ($\pm 45/90/45/0/-45/0$) _s	1.15	0.19	1.31	0.13	1.25	0.81	0.29

TABLE III: DESIGN VARIABLE VALUES FOR THE OPTIMAL DESIGN

Design variable	Skin thickness (h), mm	No. of helical rib pairs, (n)	Helical rib thickness, (t_h), mm	Helical rib height, (H_h), mm	Frame pitch, (d), mm	Frame thickness, (t_f), mm	Frame height, (H_f), mm
Optimum value	1.71	150.00	0.61	27.80	501.70	1.00	50.00

Results in Table II show that buckling is the driving criterion in obtaining the optimum. The metamodel-predicted optimum has a critical margin of buckling of 0.00 with a normalized weight of 0.29. However, when this was checked with a finite element analysis using a fine mesh, this value was found to be -0.07 that is unacceptable. This issue has to be addressed by interpreting the skin as a valid compositelaminate at the end of this Section.

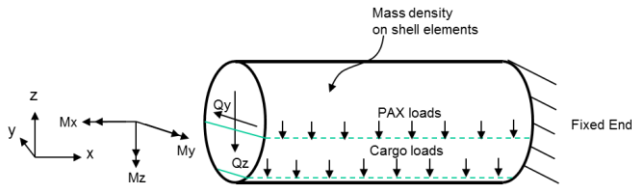


Fig. 5. Load application.

The predicted tensile strain margin of 0.20 is conservative when compared the 0.62 margin obtained by the FE analysis. The predicted compressive and shear strain of 0.23 and 1.27, respectively, are not conservative compared to the compressive strain margin of 0.08 and the shear margin of 1.09 obtained by the FE analysis. This is acceptable as these are not the critical margins. The predicted stiffness margins are the same as the margins obtained by the FE analysis but do not act as critical constraints in this design optimization problem. The design variable set for the final optimum geometry is listed in Table III. The length of the frame pitch is

The parametric optimization of the fuselage barrel was performed by a Genetic Algorithm (GA) used on the GP-derived analytical metamodels. Since a GA has good non-local properties and is capable of solving problems with a mix of continuous and discrete design variables, it becomes a good choice for the fuselage barrel optimization where one of the design variables, the number of helical ribs, is integer. The results of the metamodel-based optimization and the fine mesh FE analysis are given in Table II.

TABLE I: DESIGN VARIABLES

Design variables	Lower bound [mm]	Upper bound [mm]
Skin thickness (h)	0.6	4.0
Number of helical rib pairs, (n)	50	150
Helical rib thickness, (t_h)	0.6	3.0
Helical rib height, (H_h)	15	30
Frame pitch, (d)	500	650
Frame thickness, (t_f)	1.0	4.0
Frame height, (H_f)	50	150

501.7 mm which is close to the lower bound of 500. The resulting small triangular skin bays have a base width of 83.78 mm, a height of 501.7 mm and a small angle between the crossing helical ribs of $2\phi=9.55^\circ$. Such small and skinny-triangular skin bays are excellent against buckling. There is a good correspondence of the obtained results with the analytical estimates of DLR that produced the value of $2\phi=12^\circ$ [10].

Since the optimal design only used smeared ply properties, the skin thicknesses had to be corrected to account for a standard CFRP ply thickness of 0.125 mm. This means that the skin thickness is increased from 1.71 mm to 1.75 mm and plies of 0° , 45° , -45° and 90° orientation arranged in a balanced and symmetric laminate have to be used to comply with the aircraft industry lay-up rules and manufacturing requirements [11]-[13]. The structural responses obtained by the FE analysis with the $(\pm 45/90/45/0/-45/0)_s$ laminate skin are given in Table II.

Incorporating the ply thicknesses into the design has increased the buckling margin of safety making all margins positive. Therefore a light-weight design which fulfils the stability, global stiffness and strain requirements has been obtained.

VII. CONCLUSION

Parametric optimization was applied to the detailed design

of a fuselage barrel section by using Genetic Algorithms on a metamodel generated with Genetic Programming. The optimum structure was obtained by performing parametric optimization subject to stability, global stiffness and strain requirements, then its optimal solution and structural responses were verified by finite element simulations. The stability criterion is the driving factor for the skin bay size and the fuselage weight. By interpreting the skin modelled with smeared ply properties as a real-life composite laminate, a practical lay-up with a standard ply thickness of 0.125 mm has been obtained as $(\pm 45/90/45/0/-45/0)_s$. It is concluded that the use of the global metamodel-based approach has allowed to solve this optimization problem with sufficient accuracy as well as provided the designers with a wealth of information on the structural behaviour of the novel anisogrid composite fuselage design.

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